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# Terahertz radiation from delta-doped GaAs

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Terahertz pulse emission from four different delta-doped molecular beam epitaxially grown GaAs samples is studied. We observe a decrease of the emitted THz pulse amplitude as the distance of the delta-doped layer from the surface is increased, and a change in polarity of the THz pulses as compared to bulk *n*-type doped GaAs reference samples. The electric fields in the region of the doping layer are investigated by photoreflectance spectroscopy. A careful analysis of Franz-Keldysh oscillations observed in the photoreflectance spectra provides information about the built-in fields on both sides of the delta-doped layer.

The emission of ultrafast THz pulses after femtosecond laser pumping was recently introduced by Zhang and Auston<sup>1</sup> as a sensitive probe of the semiconductor surface region. Photoexcited carriers created near the surface are accelerated by the electric field present due to band bending. The resulting photocurrent radiates an electro-magnetic pulse possessing frequency components in the THz regime. The detailed structure of the THz pulse carries information about the built-in surface fields in the sample.

The presence of a delta-doped layer in the vicinity of the surface creates a very large field at the surface. Electric fields up to 100 kV/cm have recently been inferred from the observation of Frank-Keldysh oscillations in the photoreflectance spectra of delta-doped GaAs.<sup>2,3</sup> These characteristics of the delta-doped structures make them very interesting as sources of THz radiation, where both the high field and the high mobility should make the emitted THz amplitude greater than that emitted from bulk GaAs surfaces.

In this letter we study the THz emission from four delta-doped samples having different spacings between the doping layer and the surface. The polarity of the emitted THz pulses is found to be opposite that of pulses emitted from samples having bulk *n*-type doping. For increasing doped-layer-surface distance, we observe a decrease in the THz pulse amplitude. We find that the amplitude of the THz pulse depends linearly on the spacing between the delta-doped layer and the surface, independent of the magnitude of the associated electric field. By performing photoreflectance measurements on the same samples we are able to extract information about the built-in fields on both sides of the doping layer and correlate this information with the behavior of the THz pulses.

The delta-doped GaAs samples used in this work were grown by molecular beam epitaxy on Cr-doped semi-insulating GaAs substrates. The four delta-doped samples have the doped layer positioned at a distance, *d*, of 25, 50,

100, and 200 nm from the surface. The delta doping was of *n* type with Si as dopant. The same Si dose was used for each sample. A 1-μm buffer layer of undoped GaAs with a background *p*-type concentration of approximately  $2 \times 10^{14} \text{ cm}^{-3}$ , was grown between the substrate and the delta-doped layer. The samples were capped by identical GaAs. As reference samples for the THz experiments, we used a semi-insulating liquid-encapsulated Czochralski (LEC) GaAs sample.

The experimental setup used in the THz experiments is described in Ref. 4. The laser source was a mode-locked titanium sapphire laser producing  $\approx 200$ -fs pulses at 840 nm. The beam was gently focused to a diameter of approximately 1 mm at the sample surface. The pump power was 100 mW, corresponding to a sheet carrier density of  $1 \times 10^{12} \text{ cm}^{-2}$ . The THz signal generated from the surface propagates to a receiving dipole antenna defined on ion implanted silicon on sapphire. The receiver has a bandwidth extending to 2 THz, mainly limited by the dielectric loss in the sapphire substrate.

The photoreflectance (PR) experiments were conducted in a standard one-spectrometer configuration.<sup>5</sup> The average pump density was kept below  $1 \text{ mW/cm}^{-2}$  and the spectral resolution was kept at 0.6 nm throughout the PR experiments. The sign of the modulated reflectance signal has been taken as positive when in phase with the luminescence from the sample, and the spectra have been normalized with the reflectance spectrum.

Delta-doped GaAs has previously been studied by PR.<sup>2,3</sup> Using this technique it is possible to deduce the electric field in the region between the surface of the sample and the delta-doped layer, as well as the magnitude of the surface potential. All the PR spectra show Franz-Keldysh oscillations above the GaAs band edge, as summarized in Fig. 1. The curves are labeled with the depth of the delta-doped layer, *d*. The extremal points of Franz-Keldysh oscillation are given by<sup>6</sup>

$$m\pi = \frac{4}{3} \left( \frac{E_m - E_g}{\hbar\Omega} \right)^{3/2} - \theta, \quad (1)$$

where *m* is an integer, *E<sub>m</sub>* is the energy of the *m*th extremal

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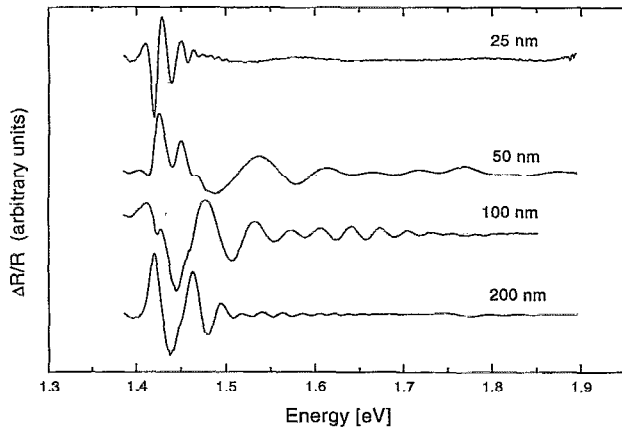


FIG. 1. Photoreflectance scan of the four delta-doped samples. The individual spectra are marked to indicate of the depth the delta-doped layer.

point,  $E_g$  is the energy band gap,  $\theta$  is an arbitrary phase factor, and  $\hbar\Omega$  is the electro-optic energy defined by

$$(\hbar\Omega)^3 = \frac{(q\hbar F_{dc})^2}{2\mu_{\parallel}}, \quad (2)$$

where  $q$  is the electron charge,  $F_{dc}$  is the electric field, and  $\mu_{\parallel}$  is the reduced electron mass in the direction of the electric field.

In Fig. 2 the values of  $4/(3\pi)(E_m - E_g)^{3/2}$  are plotted versus photon energy. The extremal points for the 200-nm and the 100-nm samples are indicated by triangles. The data follow straight lines yielding fields of 30.2 and 58.7 kV/cm for the 200-nm and the 100-nm samples, respectively. The circles in Fig. 2 are for the 50-nm sample. The last seven points, indicated by open circles, follow a straight line yielding an electric field of 106 kV/cm. The first five points indicated by the solid circles does not follow this line. The squares indicate extremal points for the 25-nm sample. The solid squares represent the extremal points of the “slow” oscillations in Fig. 1. The index,  $m$ , of the first oscillation is set to 2 because the first slow maximum is obscured by the

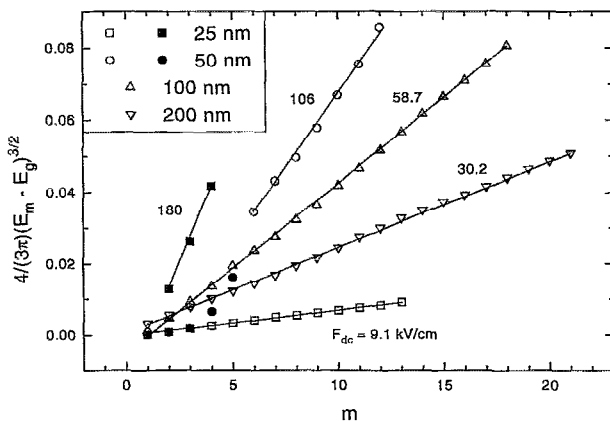


FIG. 2. The position of the extrema in the PR spectrum. The value of  $4/(3\pi)(E_m - E_g)^{3/2}$  vs  $m$  is indicated by markers. The lines show a linear fit to the data points. The slope of each of the straight lines corresponds to the electric field indicated in the figure.

“fast” component. The solid squares follow a straight line yielding an electric field of 180 kV/cm. The open squares represents the “fast” oscillations near the GaAs band edge. These data follow a straight line yielding an electric field of 9.1 kV/cm. These points also coincide with the first three points derived from the 50-nm sample.

For the  $d=25$ -nm sample we see clear features in the spectrum that originate from both sides of the delta-doped layer. The “slow” oscillations are Franz–Keldysh oscillations from the surface side of the delta-doped layer, and the field deduced from the Franz–Keldysh oscillations (180 kV/cm) is, to the authors knowledge, the highest ever reported for delta-doped GaAs structures. The “fast” component is consistent with Franz–Keldysh oscillations from the substrate side of the delta-doped layer, as will be discussed in the following.

The depletion approximation offers an opportunity to acquire a quantitative estimate of the band diagram and the electric fields on both sides of the delta-doped layer. In the delta-doped layer, the conduction band edge is very close to the Fermi level because of the high donor concentration. The high number of surface states of GaAs effectively “pins” the Fermi level at an energy  $qV_s$  below the conduction band edge. Neglecting the donor concentration, the surface field is then obtained as

$$F_s \approx -V_s/d. \quad (3)$$

The experimental values of the surface field obtained in the PR experiment are well described by Eq. (3) using a surface potential of  $V_s=0.6$ , in agreement with Ref. 2. The results of the depletion model suggest that the fields measured in the PR experiment originate from the narrow region from the surface to the delta-doped layer.

On the substrate side of the delta doping, the field is determined by the residual acceptor type impurities of the molecular beam epitaxially (MBE) grown GaAs. For a residual doping density of  $N_A=2 \times 10^{14} \text{ cm}^{-3}$ , we find a built-in potential of  $V_{bi}=1.1$  V. This corresponds to a depletion width of

$$W = \sqrt{\frac{2\epsilon V_{bi}}{qN_A}} \approx 2.7 \text{ } \mu\text{m} \quad (4)$$

and an electric field that varies linearly from its maximum value  $F_m$  near the delta-doped layer to zero in the bulk. The magnitude of the maximum field is given by

$$F_m = \frac{qN_A W}{\epsilon} \approx 7.7 \text{ kV/cm}. \quad (5)$$

Since the depletion width is much larger than the absorption length, the field can be considered equal to  $F_m$  in the optically probed region. Furthermore, we notice that  $F_m$  is independent of the position of the delta-doped layer. The calculated value of  $F_m \approx 7.7$  kV/cm compares favorably with the field of 9.1 kV/cm deduced from the “fast” oscillations in the PR spectrum of the 25-nm delta-doped sample. We propose that these oscillations are due to the Franz–Keldysh effect in the depletion region on the substrate side of the delta-doped layer.

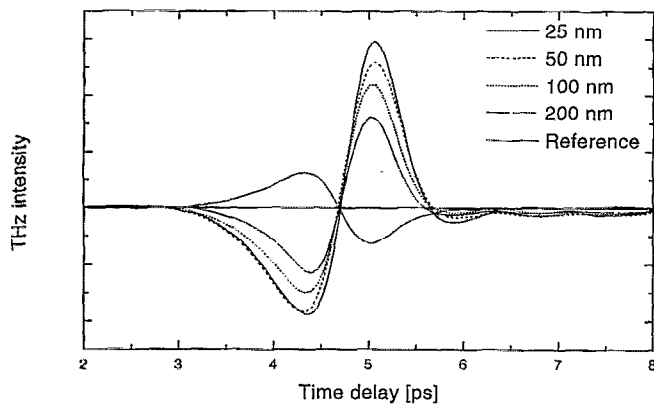


FIG. 3. THz pulse radiated from the four delta-doped samples and the GaAs reference sample with the Ti:sapphire laser operating at 840 nm.

THz signals radiated from the delta-doped samples upon laser pumping are shown in Fig. 3. The curves are labeled to indicate the type of sample. The THz signal shows a characteristic damped oscillation with an approximate period of 2.6 ps, which is related to the dynamics of the excited carriers. Also shown are pulses radiated from the LEC GaAs reference sample. It is observed that the THz pulses from the delta-doped samples show the opposite polarity of the THz pulse emitted by the pure GaAs sample.

We show in Fig. 4 the rms values of the THz pulses emitted from the four delta-doped samples as a function of the position of the delta-doped layer. The straight line is a fit to the data and is explained in the following way: The source current responsible for the radiated THz pulse originated

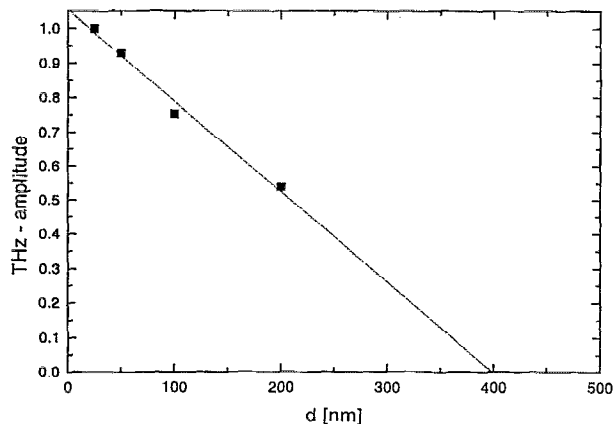


FIG. 4. Root-mean square values of the THz pulses emitted from the delta-doped sample relative to the  $d=25$ -nm sample as a function of delta-layer depth. The line represents a linear fit to the data.

from both sides of the delta-doped layer. The surface and substrate side contributions have opposite sign; the total THz signal is the sum of these contributions. The contribution to the THz signal from the surface side of the delta-doped layer is proportional to the depth of the delta-doped layer as discussed in Ref. 1. Since the depletion width on the bulk side is much larger than the absorption length, which in turn is larger than the depth of the delta-doped layer, the contribution from the substrate side of the delta-doped layer is approximately independent of the delta-layer depth. The two terms cancel out when the depth of the delta-doped layer equals one half of the absorption depth as reflected by the extrapolation to zero THz amplitude in Fig. 4.

The sign of the electric field radiated from the surface, and correspondingly the direction of the photocurrent can be determined from the measured pulses by calibrating the response of the detection system with a biased THz antenna, where the direction of the current is fixed by the polarity of the applied bias. We find that the observed polarity of the pulses radiated from the delta-doped samples corresponds to a net current directed toward the substrate. This is consistent with the majority of the THz signal arising from the substrate side of the delta-doped layer providing evidence of the importance of the electric field distribution at the delta-doped region to THz pulse generation.

In summary, we have performed photoreflectance and THz experiments on four delta-doped GaAs samples. The novel combination of the photoreflectance technique and the THz experiments has proven useful in probing the electric field distribution of these structures. The electric fields on both sides of the delta-doped layers are extracted from Franz-Keldysh oscillations observed in the photoreflectance experiments. The results of the THz experiments are qualitatively explained in a model where the radiated THz amplitude is proportional to the width of a region generating a current following fs laser excitation. Our observations support the claim by Zhang and Auston<sup>1</sup> that the THz amplitude is independent of the magnitude of the electric field. The reason for this is not fully understood. However, the sign of the electric field is directly reflected by the phase of the emitted THz pulse.

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